Phase Centre Variations in Adaptive GNSS Antenna Arrays

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Overview

- Motivation
- Introduction to concept of antenna phase center
- Problem of phase center variation
  in satellite navigation
- Practical results with array receiver demonstrator
- Summary and outlook

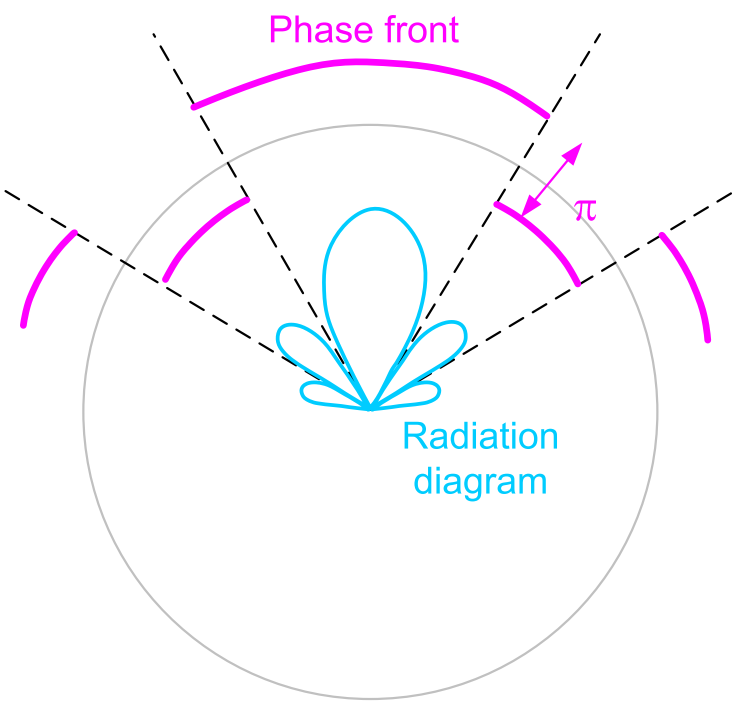
Motivation

- Adaptive antenna is a promising technology for improving performance of a Global Satellite Navigation System (GNSS) in difficult signal environments with radio interference or/and multipath

- For high-end applications, the biases introduced by an adaptive antenna into the code-phase and carrier-phase measurements should be known and compensated. The tolerable residual measurements errors is at cm-level for code- and mm-level for carrier measurements

Concept of Antenna Phase Centre (1)

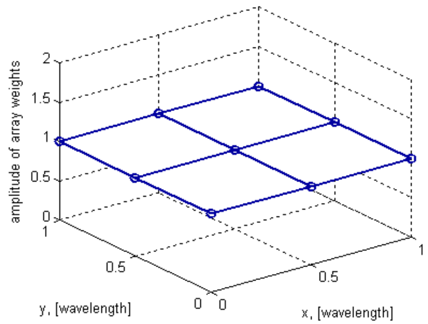
- Phase centre (PC) of an antenna is referred to as a point from which the field apparently emanates
- When emitted, far-field phase fronts (equiphase contours) are spherical or substantially spherical if PC is situated in the origin of the coordinate system



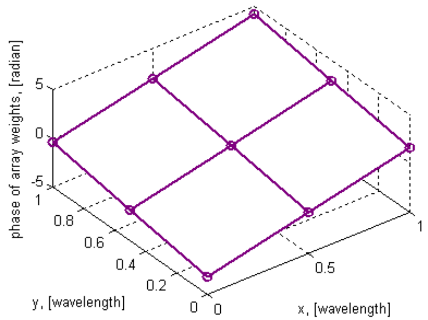
Concept of Antenna Phase Centre (2)

- Existence condition of a unique phase centre of an antenna [Gusevsky,1991] : it exists and is located in the geometric centre of the aperture if (i) the amplitude distribution of the field in the aperture is an even function of the coordinates (ii) the phase distribution is an odd function
- For antenna arrays, the existence condition is an analogue of the condition for a linear phase FIR digital filter
- In practice, there are no antennas with a unique phase centre. However, a partial phase centre can be found that produces the smallest slope of the far-field phase in a given direction

Example: 3-by-3 array with the field distribution fulfilling the condition



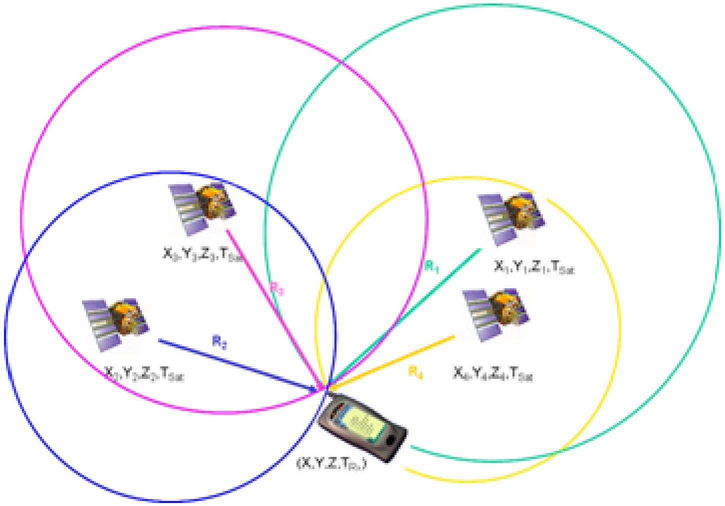
Amplitude

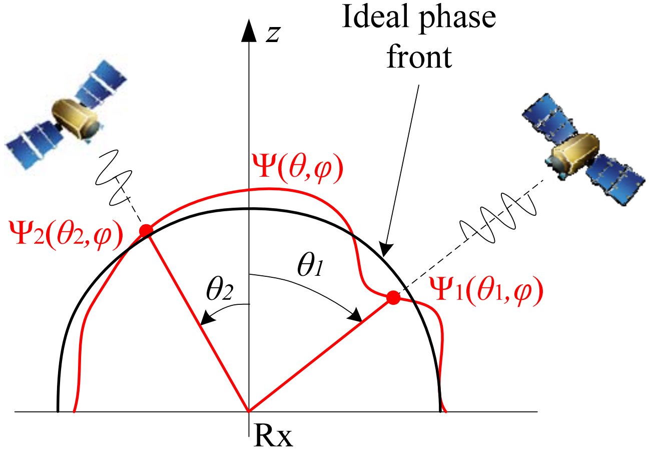


Phase

Problem of Phase Centre Variation (1)

- Positioning in satellite navigation is based on the range measurements to the satellite in known locations. The measurements are performed by utilizing
  (i) phase (delay) of a PRN code, and
  (ii) phase of the signal carrier
- The satellite signals coming from different directions experience different delays of the PRN code- and carrier phases.
  This can be interpreted as the effect of the variation of partial phase centers





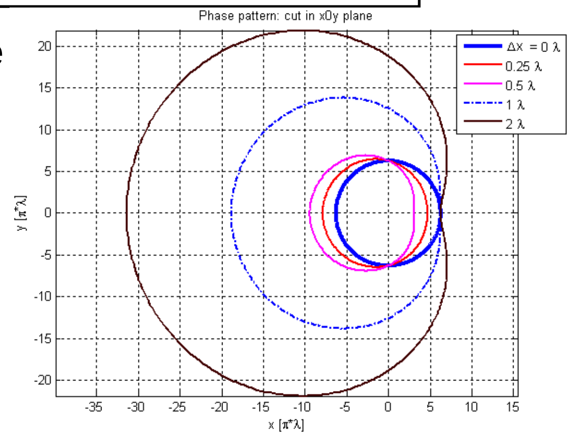
Problem of Phase Centre Variations (2)

- The positions of the partial phase centres can be estimated by fitting the "ideal" curves for phase and group-delay patterns to the actual ones
- However, it is often sufficient to find the phase- and group delays introduced by the antenna system

Example 1: "Ideal" far-field phase

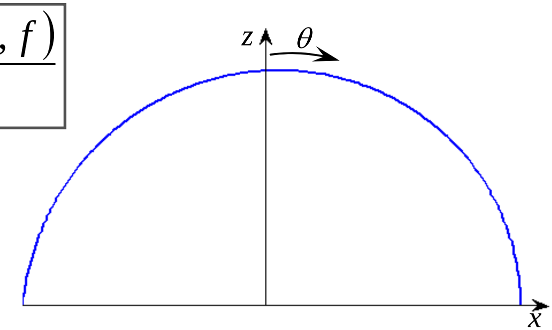
$$\psi(\theta,\varphi)=\psi_0+ k(x\cos\varphi\sin\theta+y\sin\varphi\sin\theta+z\cos\theta)$$

x, y, z = phase centre coordinates



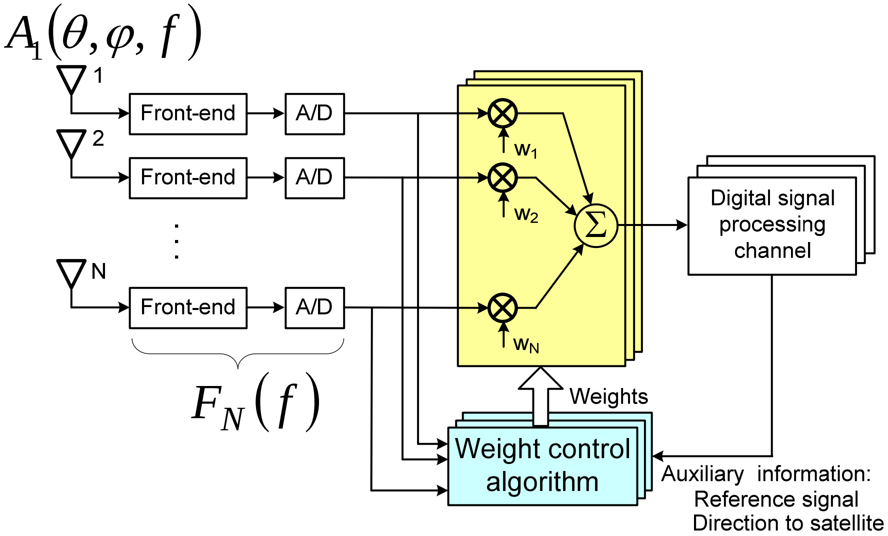
Example 2: "Ideal" group-delay pattern

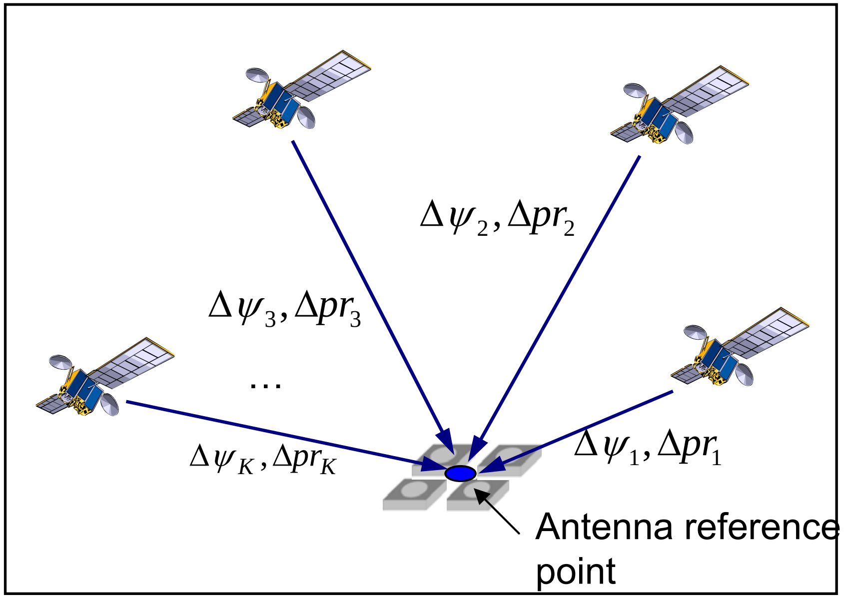
$$\tau(f,\theta,\varphi)=\frac{c}{2\pi}\frac{d\psi(\theta,\varphi,f)}{df}$$



Problem of Phase Centre Variations (3)

Block diagram of a GNSS array receiver





System response of a beamforming channel (neglecting non-linear effects)

$$H(\theta,\varphi,f) = \sum_{n=1}^{N} w_n A_n(\theta,\varphi,f) F_n(f)$$

- phase delays $\Delta\psi_k$
- group delays Δpr_k

Effect on positioning and timing:

$$\begin{bmatrix} \delta x \\ \delta y \\ \delta z \end{bmatrix} = \left(\mathbf{G}^T\mathbf{W}\mathbf{G}\right)^{-1}\mathbf{G}^T\mathbf{W}\,\delta\mathbf{p}, \quad \mathbf{G} = \begin{bmatrix} (-\vec{\mathbf{1}}^{(1)})^T \\ (-\vec{\mathbf{1}}^{(2)})^T \\ \vdots \\ (-\vec{\mathbf{1}}^{(K)})^T \end{bmatrix}$$

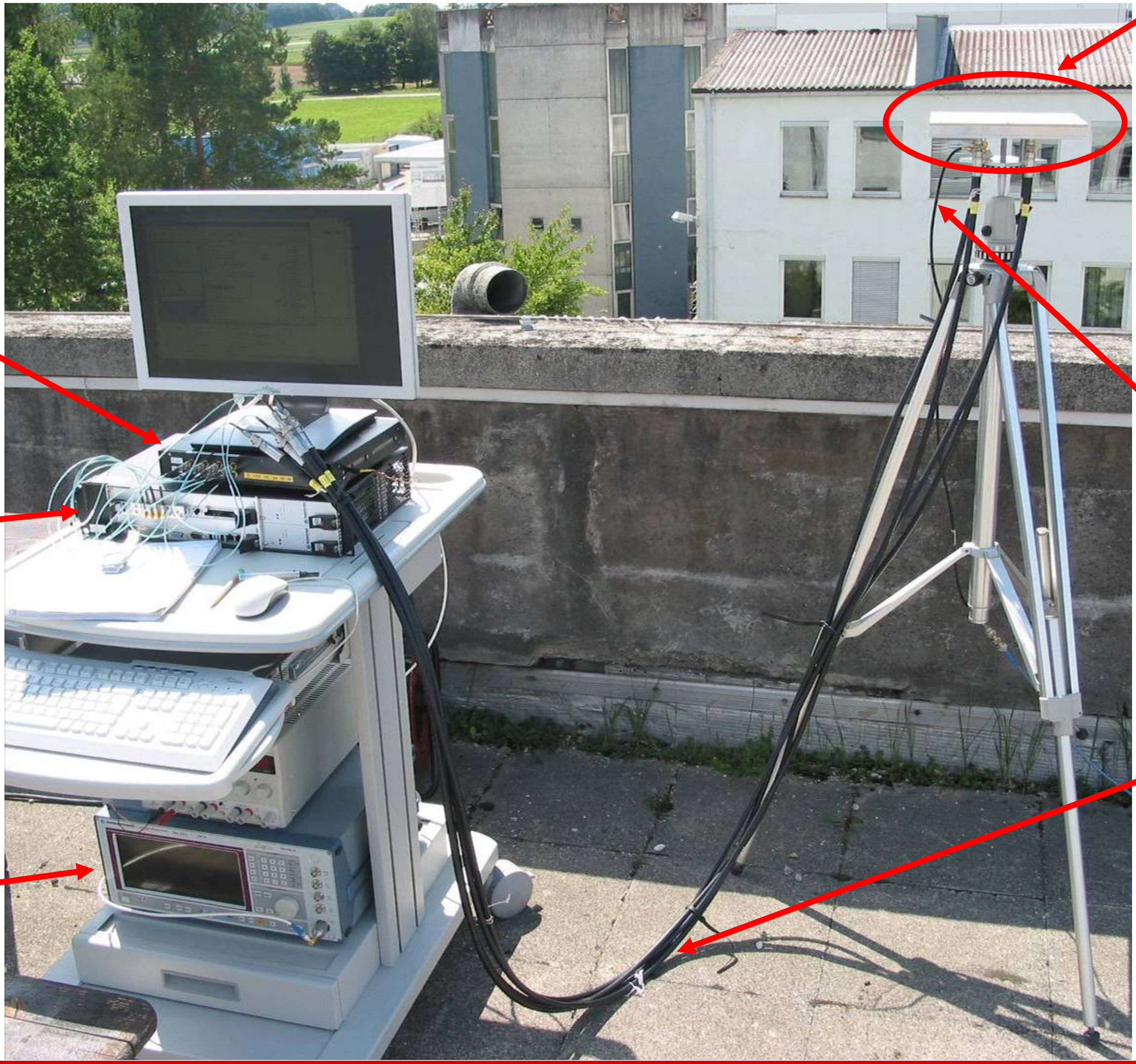
Geometry matrix

Practical Results (1)

Multi Channel Front End

FPGA and Embedded PC

LO-Generator



2-by-2 Antenna-Array

Cal. Signal

3 m RF-Cables

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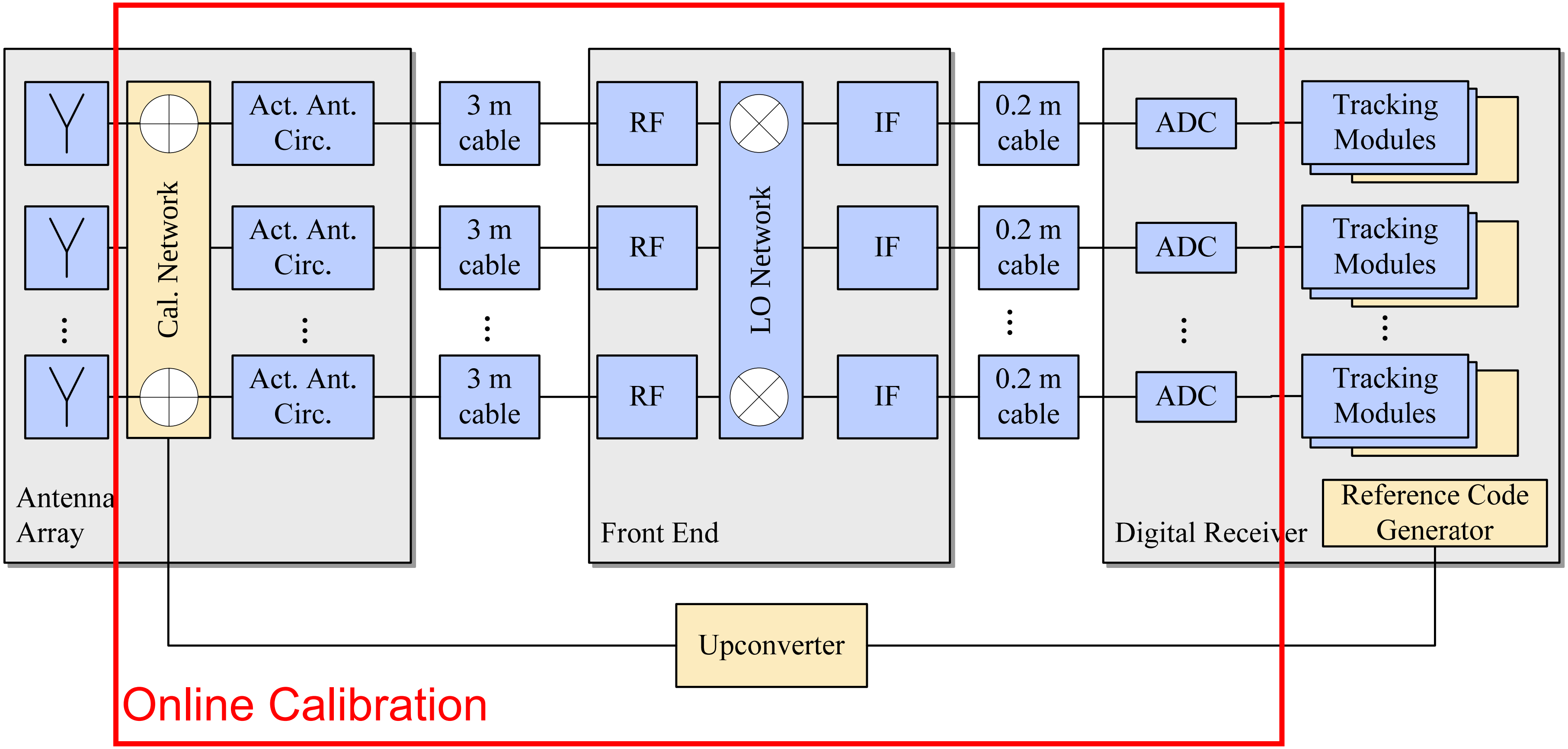
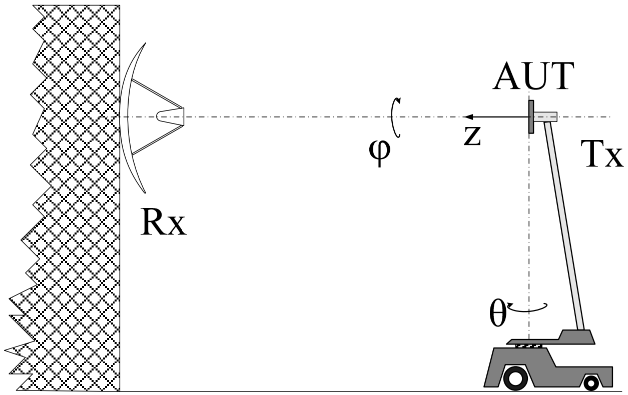
Practical Results (2)



Practical Results (3)

- Measurement grid:
  $\Delta\theta = 1°$, $\Delta\varphi = 5°$
- Two step-motors
- One of the motors (azimuth angle) is at height of 7.5m
- Another motor (elevation angle) is in the base of the tower on the carriage

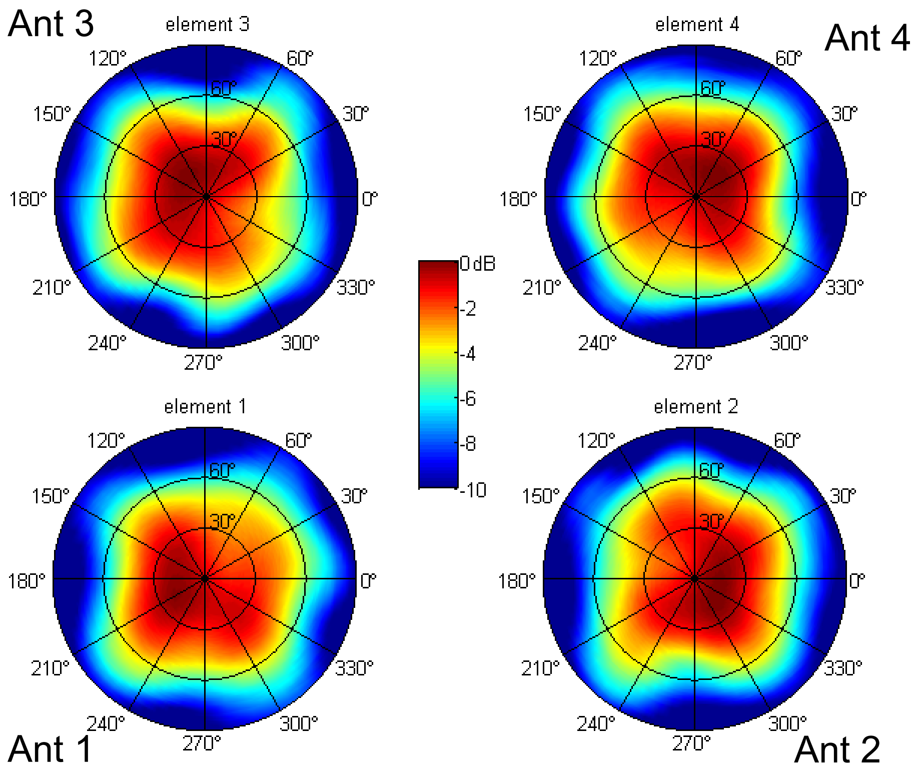


Open range antenna measurements

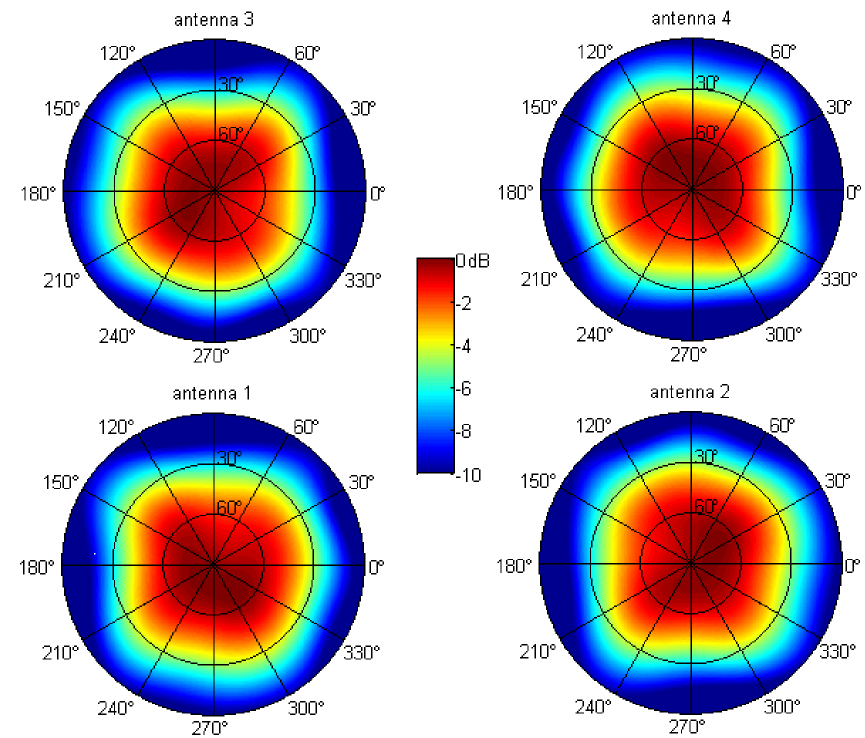
Practical Results (4)

Normalised gain patterns:

measured



simulated, HFSS



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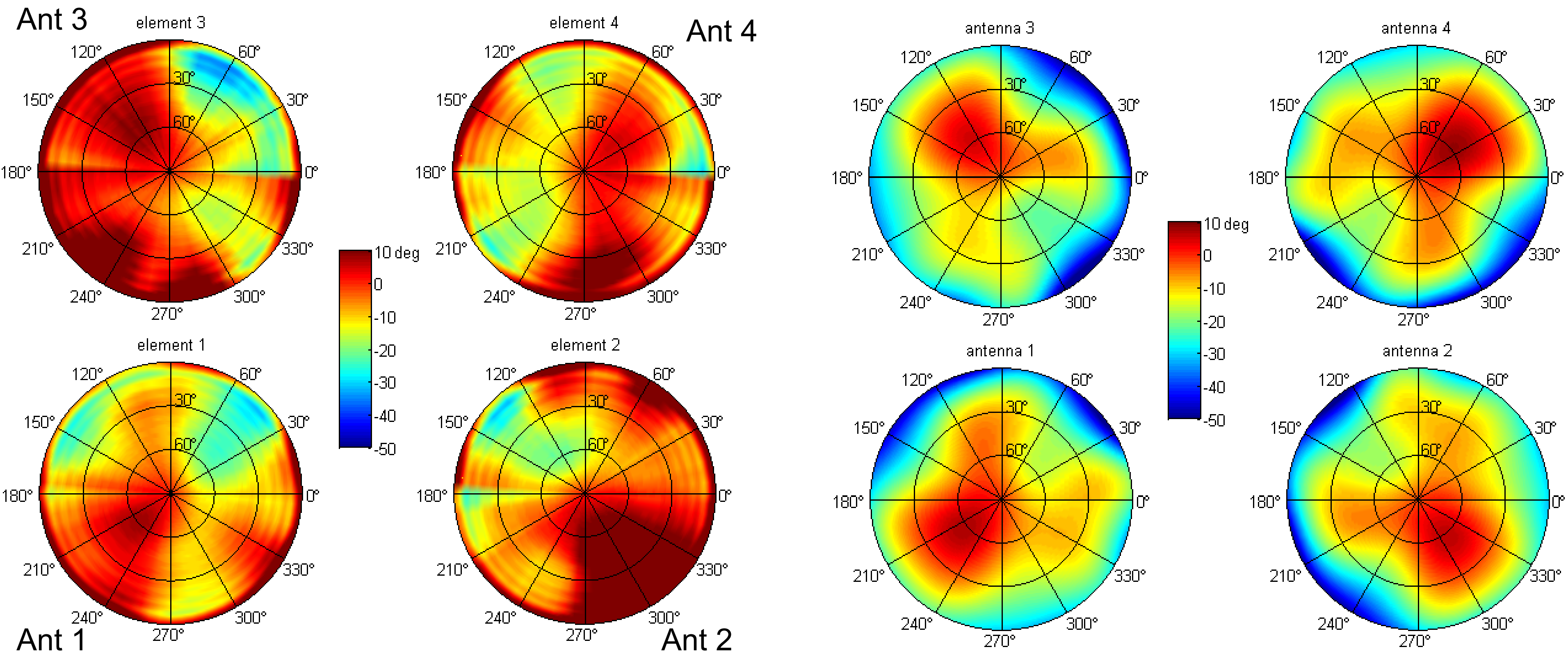
Practical Results (5)

Phase patterns:

measured

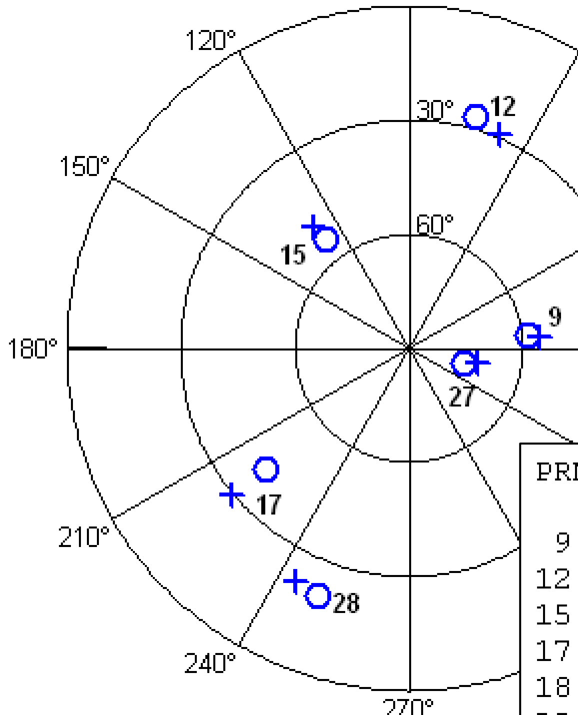
simulated, HFSS



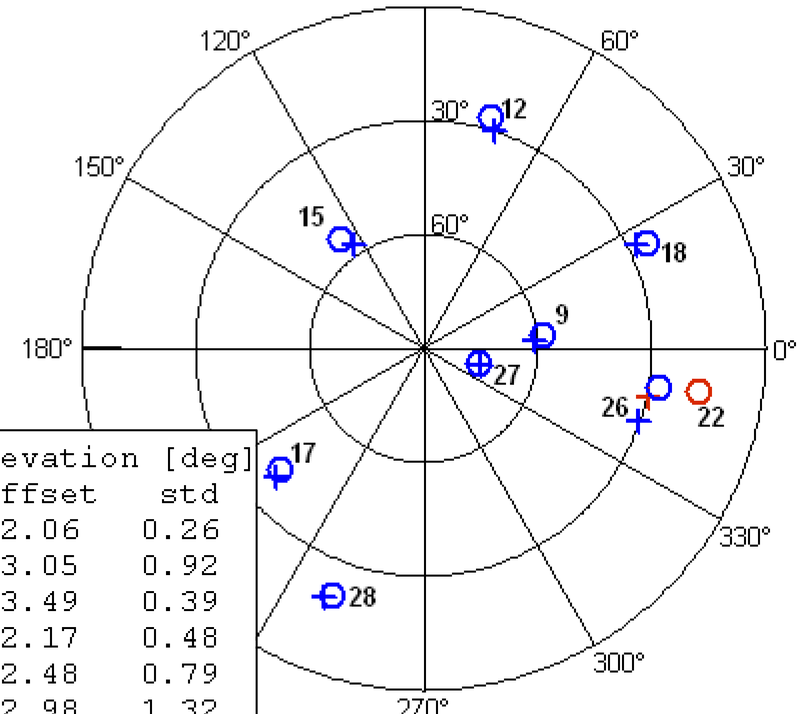
Practical Results (6)

Direction-of-Arrival estimation using 2D unitary ESPRIT:

not accounting for inequality of array elements



accounting for actual patterns of array elements (measured)



PRN	Azimuth [deg] offset	std	Elevation [deg] offset	std
9	-1.85	0.40	-2.06	0.26
12	-1.95	1.21	-3.05	0.92
15	-3.21	0.40	-3.49	0.39
17	0.66	0.33	2.17	0.48
18	0.92	0.40	-2.48	0.79
22	-3.68	0.81	-12.98	1.32
26	-9.12	0.54	-2.94	0.86
27	-2.20	0.61	0.67	0.27
28	-1.36	0.47	1.53	1.22

Practical Results (7)

Deterministic beamforming

$$w_i = \mathrm{conj}\left\{ \exp\left(j\frac{2\pi}{\lambda}\left(x_i \cos\varphi \sin\theta + y_i \sin\varphi \sin\theta + z_i \cos\theta\right)\right) AP_i(\theta,\varphi)\right\}$$

Linearly Constrained Minimum Variance (LCMV) beamforming

$$\min_{\mathbf{w}} E\left\{\left|y(t)\right|^2\right\} = \min_{\mathbf{w}} \mathbf{w}^H E\left\{\mathbf{x}(t)\,\mathbf{x}^H(t)\right\}\mathbf{w} = \min_{\mathbf{w}} \mathbf{w}^H \mathbf{R}_{xx}(t)\,\mathbf{w}$$

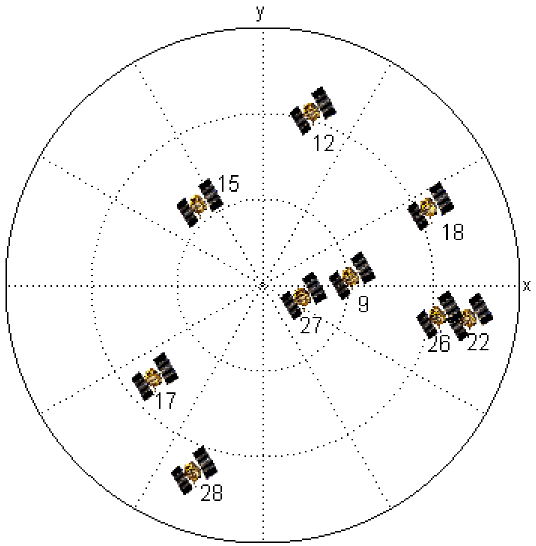
subject to linear constrains: $\mathbf{a}(\theta,\varphi)\,\mathbf{w}^H = 1$ -> MVDR beamformer

or $w_1 = 1$ -> MV adaptive nulling

Minimum Mean Square Error (MMSE) beamforming

$$\min_{\mathbf{w}} E\left\{\left|r(t) - y(t)\right|^2\right\} = \min_{\mathbf{w}} E\left\{\left|r(t) - \mathbf{w}^H \mathbf{x}(t)\right|^2\right\}$$

Practical Results (8)



PRN	Carrier-phase measurement error [mm]					
	Deterministic beamforming		Minimum mean square error beamforming with temporal reference		Beamforming with spatial reference from direction finding	
	$\delta\psi$	std($\delta\psi$)	$\delta\psi$	std($\delta\psi$)	$\delta\psi$	std($\delta\psi$)
9	0.00	0.00	9.5	54.7	0.054	0.001
12	0.00	0.00	-12.2	32.6	-0.013	0.216
15	0.00	0.00	-0.0	55.9	0.056	0.028
17	0.00	0.00	8.3	56.3	0.051	0.040
18	0.00	0.00	-4.4	55.7	-0.874	0.186
22	0.00	0.00	-4.4	52.9	-0.554	0.246
26	0.00	0.00	12.2	53.2	-0.201	0.150
27	0.00	0.00	41.6	34.2	-0.042	0.031
28	0.00	0.00	0.0	74.8	-0.177	0.272
Positioning error [mm]						
	mean = 0.00 std = 0.00		mean = 17.9 std = 57.7		mean = 0.44 std = 0.18	

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Summary and Outlook

- Because of the adjustable reception pattern, the calibration of the phase centre variations of an adaptive antenna is more complex compared to fixed-pattern antennas
- Efficient calibration of the phase centre requires precise measurements both of the field patterns of the array elements as well as of transition characteristics of the RF front ends
- Potentially, if this information is available, the positioning error with carrier-phase measurements in an adaptive array receiver can be kept at mm-level by using constrained beamforming techniques
- The positioning error with code-phase measurements have still to be investigated in future studies

Thank you for attention!